EXPLORING 3D AUDIO FOR BRAIN SONIFICATION

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ABSTRACT

Brain activity data, measured by functional Magnetic Resonance Imaging (fMRI), produces extremely high dimensional, sparse and noisy signals which are difficult to visualize, monitor and analyze. The use of spatial music can be particularly appropriate to represent its contained patterns. The literature describes several research done on sonifying neuroimaging data as well as different techniques to use spatialization as a musical language. In this paper, we discuss an artistic approach to fMRI sonification exploiting new compositional paradigms in spatial music. Therefore, we consider the brain activity as audio base material of a the spatial musical composition. Our approach attempts to explore the aesthetic potential of brain sonification not by transforming the data beyond the recognizable, but presenting the data as direct as possible.

1. INTRODUCTION

Functional Magnetic Resonance Imaging (fMRI) provides the user with information on the location of functional activations in the different regions of the brain with high spatial resolution. The resulting data is highly dimensional, sparse and noisy, and is difficult to monitor and detect structures or patterns. This fact has motivated the approach to improve the exploratory data analysis. The main goal is to use sound to render the original data in a suitably transformed way, so that we can invoke our natural pattern recognition capabilities to search for regularities and structures.

In particular, these capabilities and mechanisms are triggered involuntarily during the act of listening to what we perceive as music. When listening to music, the brain constantly estimates the continuation of a musical gesture. We find pleasure in the encounter of a musical pattern and so this search for connections and an apparent message in music comes natural to us. At the same time, interest needs to be maintained by providing surprises and unforeseen developments that make us reconsider our previous estimations keeps the music engaging. The main job of a composer is to skillfully play with this expectation and keep up the interest by violating the predictions made and breaking the patterns.

Sonification in music makes use of patterns contained in the data to be sonified. A composer of algorithmic music consciously takes the decision to step back from his foremost compositional responsibilities and lets the algorithm and the data take control of the musical creation to a large part. Algorithmic composition requires human intervention on higher, more abstract levels [1]. Decisions such as the proper mapping of parameters, processing and filtering of inaudible data need to be made, while the minor details are left to chance. Listening to this style of music may serve both an aestehtic and scientific purpose. For their database of *Sonification in Music*, Schoon and Dombois [2] define three criteria for inclusion of a work: the transformation from inaudible to audible frequency, the acquisition of knowledge through the act of listening, as well as the development of listening techniques that are subject to scientific validation.

In this paper, we discuss an artistic approach to fMRI sonification that exploits new compositional paradigms in spatial music, attempting to establish the physical space around the listener as a musical language of its own. That is, beyond the ability to utilize frequency, rhythm and timbre among other musical parameters, the process of spatializing music is not just a tool for further clarification of the sonic material, but part of the compositional process and is considered musical gesture in itself. In a sense, a sonorous gesture in physical space is comparable to a melody and closely linked to timbre and rhythm.

Even though the human hearing system is known to be able to decode and interpret complex auditory scenes [3], the more structured the representation of the sonified data, the better the accessibility and intelligibility of the chosen process. Hence, presenting both distinct data and interpretations of the data in respective, designated musical dimensions aids in bringing clarity to the audible scene. Adding the ability to spatialize music in full, continuously and freely moveable three dimensional space opens new possibilities to data sonification and changes the way sounds are interpreted in relation to their perceived spatial location.

2. BACKGROUND

2.1. Sonification for data exploration

With abundance of high-dimensional data, auditory data exploration has become an important tool to comprehend such data and to uncover its structures and patterns [4, 5]. Thus, sonification has expanded beyond the classic process monitoring applications and many researchers among different fields are currently researching in this area.

Vogt et al. [6] used sonification to understand lattice quantum chromodynamics (QCD) as a representation of a 4 dimensional space; Grond et al. [7] implemented a combined auditory and visual interface to help browsing ribonucleic acid (RNA) structures; Winters et al. [8] simulated through sound the phase transition that occurred shortly after the Big Bang; Bearman [9] used sound to represent uncertainty in future climate predictions; Alexander R. et. al [10] was able reveal new insights into data parameters for differentiating solar wind types, by audifying and listening to 13 years of heliospheric measurements.

Sonification is particularly appropriate to improve the understanding of neuroimaging data, which is naturally multidimensional. There have been several studies that have focused on analysing the data obtained from Electroencephalography (EEG) measurements. One of the first attempts to auditory EEG exploration was reported in 1934 by E. Adrian and B. Matthews [11]. For their research they measured the brain activity from a human subject by electrodes applied to the head, and the channels were viewed optically on bromide paper using the Matthews oscillograph, while being directly transduced into sound. More recently, T. Hermann et al. have presented different strategies of sonification for human EEG [12, 13, 14, 15] and Gomez et al. [16] studied different approaches to fMRI brain data sonification.

Music has also been used to represent human EEG. One example is the work of D. Wu et al., representing mental states by using music [17]. The EEG features were extracted by wavelet analysis and they would control musical parameters such as pitch, tempo, rhythm, and tonality. To give more musical meaning, some rules were taken into account like harmony or structure. One of the main challenges of this work was to find the precise trade-off between direct sonification of the features and music composition.

One of the most relevant musical outcomes was the concert of sonification at the Sydney Opera House, for the ICAD 2004 [18]. Ten pieces of music were composed from an EEG data set of a person listening to a piece of music. Whilst performed the audience stood immersed during the concert in a 16.2 dome of speakers arranged to mimic the positions of EEG electrodes on the scalp. Although most participants made use of the speaker configuration, the musical impact of placing specific sound material in each respective location is rarely discussed. Sonically, section 1 of the piece *The Other Ear* by John A. Dribus shows similarities, in the sense that he creates a fast swirling sensation to represent the brain's activity.

2.2. Spatialization as a musical language

Space is present in most musical vocabulary, as well as projected into many other musical characteristics and parameters. All acoustic instruments have physical dimensions that place certain pitches to unique physical locations. Not just because of this is pitch mostly described with being *high* or *low*; we naturally associate high frequencies as coming from above and vice versa [19]. Moreover, the term 'space' is used in many musical contexts besides meaning actual physical space. Musicologists may refer to tonality as *pitch space*, or to orchestration as *timbral space* [20]. In his writing on space-form and the acousmatic image [21], Smalley presents a new musical taxonomy to compliment qualities specific to electro-acoustic music and bases is completely on the notion of space in music. The spatial development of a sound and its timbral development, the *spectromorphology* as he coins it, become one. Hence, the interpretation of a sound's more traditional audible qualities and the space it occupies are fused together.

Space and the concept of spatialization in electronic music today is a substantiated aspect of the music and is used in a unique and radically different way compared to an previous acoustic effort [22, 21, 23]. As Normandeau points out, the development of the loudspeaker had a fundamental impact on the way composers see space [23]. Being able to play any sound or timbre, especially sharing the exact same signal as another loudspeaker, makes this electronic device a unique instrument. If two loudspeakers play an identical sound the brain will fuse these two signals together, making it appear for this single sound be coming from the space between the speakers. An imbalance of amplitude between the speakers moves the sound from one speaker to another and makes the space in which the sound can travel *continuously*. Hence, the realization that a massless, virtual sound source may travel at virtually any speed to any place had a significant impact of musical thinking in the 20th century.

While the above technique, also known as stereo panning, is based on how the brain combines the auditory signals coming from both ears, not all spatialization technologies make use of these psychoacoustic principles. *Wave Field Synthesis* (WFS), in particular, tries to reconstruct the original wavefront of the virtual source from speaker array onwards [24]. Unfortunately, this requires a large amount of speakers and exhibits spatial aliasing above a certain frequency, depending on the size and proximity of the speakers. *Ambisonics* is another sound field reconstruction method but driven by psychoacoustic amplitude panning techniques, similar to stereophony [25]. Compared to *Vector Based Amplitude Panning* (VBAP), it has with a more uniform phantom image but suffers from spatialization blur [26]. In turn, VBAP, being more closely related to stereophony, triangulating the signal between the three nearest speakers [25], demonstrates a higher positioning accuracy.

2.2.1. Cultural developments in spatial music

As of the 20th century, the spatialization of music has received much focus since the dawn of the modernist period, especially with technological advances in sound reproduction techniques and electro-acoustic music on the music's increasing popularity around the 1950's [22, 27]. But the notion of space in musical composition goes back farther than one might suspect at first. Traces can be found starting from the deliberate separation of ensemble parts to articulate antiphonal compositions in biblical times [28], continuing with architecturally motivated compositions, over symbolical spaces and up to virtual soundscapes.

Around the 16th century, antiphonal psalmody heightened with the popularization of the polychoral style, specifically in Venice. The architecture of the venetian Basilica San Marco, with its two spatially separated choir lofts, is said to have inspired composers Adrian Willaert and, most famously, Giovanni Gabrieli to make impressive use of a technique known as *cori battente* or *cori spezzati* for dramatic spatial effects [26, 28, 29]. Although the use of space played an important role in their music, exact spatial arrangements were usually not indicated in the score [22]. It was usually separate the individual groups spatially, meaning that space was merely an implement for a heightened experience as opposed of true compositional concern.

While composers of the classical period showed little interest in spatial effects, there were notable exceptions, however. Wolfgang Amadeu Mozarts Serenada Notturna (1776) for two small orchestras and Notturno (1777)[1] for four Orchestras, demonstrate a tight interweaving of physical space with the music through motivic segmentation and dynamic interplay. He creates echo effects by not simply repeating phrases with each respective orchestra delayed in time, but considers dynamics, masking effects and gradually adds mutes to more instruments in each repetition to denote a gradual darkening at each reflection [29]. Later on, romantic composers would utilize spatial effects for programmatic

[1] Mozart's quadrophonic orchestra piece may sometimes be (strictly speaking, incorrectly) labeled Serenade, such as it is the case in [29] and [26]

purposes, such as the apocalyptic trumpets in Hector Berlioz' *Requiem* (1837) [30], or the use of off stage ensembles, as it is the case in the *finale* in Gustav Mahler's *Symphony No. 2* [26].

Having composed more than half his catalogue of work with deliberate spatial intentions, Henry Brant was one of the first to base his compositional methodology around the musical potential of space. His main concern was the clarification of dense textures through spatial separation [31]. He would mainly approach this problem by spatially separating the instruments into timbral groups to achieve the highest sonic distinction and prevent an effect similar to stereo panning. Furthermore, seating plans were often precisely indicated, which made his compositional techniques possible, such as trajectories and *travel and filling-up*, a gradual engulfment in sound by successively adding instruments to the overall sounding cluster.

But it was not until the introduction of the loudspeaker that the use of space in music was completely revolutionized. With the absence of harmony in atonal music and the replacement of pitch by concrete sounds in the first half of the 20th century, composers were in need of other musical parameters to communicate their compositional intentions. Edgar Varèse thought of sound as a musical object that "[...]flow, change, expand and contract, yet they have a certain tangibility, a concreteness established by clearly defined boundaries." [22]. For the Phillips Pavilion at the 1958 Brussel World Fair, he used an estimated 350 speakers to create sonic trajectories as a central element to his specifically composed *Poème Électronique* [32].

For Karlheinz Stockhausen, the spatial parameter was an inherent part of a sound and was fully integrated into *Total Serialism*. His acclaimed composition *Gesang der Jünglinge* (1956) was originally written for six channels and the serial spatialization of the sound is said to be the most fascinating features [33]. He created both electronic and orchestral pieces with clear spatial intentions in mind, such as *Gruppen* (1955-57) for three orchestras. For the Osaka World Fair in 1970, Stockhausen built the first fully spherical concert hall and created the ability to spatialize sound freely in all dimensions, even below the listener. He divided the space vertically into layers, which were individually treated in the score, with specific interpolative symbols between them [34].

Contemporary trends in spatio-musical composition turn away from a mere trajectory-oriented thinking look more at space itself as a compositional mean. During the performance of *HPSCHD* (1967-69), John Cage forced the listener to use his directional hearing and decide what to listen to by bombarding him with sounds during a "[...]five hour multi-media extravaganza[...]" [22]. Alvin Lucier famously made space his instrument in *I am sitting in a room* (1969), amplifying the rooms resonant frequencies by successively projecting and re-recording an initial phrase. Kerry Hagan, in turn, engages in textural composition [35], creating new, imginary spaces by engulfing the listener with stochastically placed granules. Putting the listener into the role of the composer, Ryoji Ikeda plays with the perception of space in *db* (2012), as the projectied composition of sine tones through a parabolic speaker is modified through ones own movement in the Hamburger Bahnhof, Berlin, as well as the reflections of other visitors that walk through the sonic beam.

Lastly, Smalley [21], already mentioned above, recognizes the ability of space to change the sounds spectromorphology. Space is not just a parameter the composer can change at will, one needs to be aware of the impact it has on the sound and the changes that happen to the actual music. Smalley coined the term *spatiomorphology*, referring to space as an appreciative experience in itself. He distinguishes spatiomorphology from using space only as means to enhance the spectromorphology. Simply put, this is where he delineates space from being a mere effect as opposed to a parameter suitable for musical expression.

2.2.2. *Perception of spatio-musical gestures*

Spatial listening is often dealt with the well known binaural cues that describe our ability to make use of our spatially separated ears and shape of our cochlear. But differences in time, level and spectral content are only half the truth. The localization models usually consider an isolated part of the frequency spectrum and would relate to real world situations only if the brain would receive a single anechoic source. Instead, our ears are constantly bombarded with many different sounds from all directions simultaneously.

To separate and localize cohesive, individual entities in this frequency agglomerate coming in through two small openings in our head, Bregman formulated a theory called *Auditory Scene Analysis* (ASA) [36]. Its essence builds on the five founding principles of Gestalt theory around which the theory of grouping and segregation, separating the figure from the ground, are formed [37]: *Similarity*, *Proximity*, *Continuity*, *Common Fate* and *Symmetry & Closure*. Segregation is caused through contrast. Two objects separate one from another not from their relation to each other, but in their relation to their background. For this, Bregman [36] defines a perceptual distance d, that describes a weighted distance between several comparative auditory dimensions, such as frequency or time.

ASA is based on two auditory grouping phenomena: Primitive segregation describes our natural abilities to segregate sounds in the environment from one another, similar to how Gestalt theory describes the urge to see patterns. Spatial cues are a major component in the process of primitive segregation and include both spatial location and spatial continuity among other cues. [37]. *Schemas* come into play where primitive segregation fails, as an additional model of learning, a way of discerning learned patterns from previous events that involved attention and may regroup previously, primitively segregated scenes.

But, beyond ASA, lie higher levels abstractions of our spatial perception. Listening to sounds in space is not fulfilled until we create a mental map of the auditory scene that we may then interpret. Phenomenology, for example, calls for time being the main mediator of this experience and the notion of space as a personal, egocentric perception with movement being the essential bodily experience [22]. This means that spatial perception – spatial awareness is not just individual, but acquired and learnable.

Even though the identification of spatial gestures as a musical act might be alien to some, the musical intentions behind the spatialization of Varèse and Stockhausen, for example, may be understood, if not personally, then culturally, on a larger time scale. Cage and Ikeda, for example, deliberately turn the focus onto the space by reducing other parameters either through overload or reduction. Music that is primarily concerned with space, but fails to address the spatial engagement will be completely misinterpreted. This form of reduced listening can be compared to that proposed in *musique concrète* [38]: aural spatial perception lies within this (usually) subconscious realm of *detectability* [36]. By putting the listener into a reduced state of mind, the composer may push his intentions into the categories of *perceptability* and *desirability* [38] and engages the listener in *attentive listening* [39].

While, at first, spatial music may seem as if it is a pure sensory experience, one just needs to look at visitors that stands in awe of the auditory space of a cathedral, the reverberation and the soundscape of small footsteps in the distance, the mumbling of soft prayers, the occasional camera clicking away. "In many situations, listeners may not be consciously aware of the affect induced by listening to engaging sound or spaces." [39]. Through reduction of other musical parameters the audience has to come to a conclusion that it was not the sounds that moved them – it had to be the space. The composer can steer the the attention to shift the listener from the *detection* of space to the attentive mode of *perception*, but the language of [...] high-impact, emotionally engaged listening [39] can only come from a rich pool of culturally established norms – and a true musical spatial language is still to be established.

3. BRAIN DATA

All the data used for this article was created during the experiments done by Grahn and Rowe in 2009 [40]. In their work they used fMRI images to study the perception of rhythm in musicians and non musicians. In their experiments, several subjects had their brain activity measured, while exposed to volume accented and duration accented rhythmic stimuli.

Every brain image obtained, contained thousands of "voxels" (Volumetric Picture Element), that have been filtered to reduce random noise in the image improves the ability of a statistical technique to detect real activations and reject false ones. Spatially smoothing each of the images improves the signal-to-noise ratio (SNR), as well as temporally smoothing avoids a number of slow "scanner drifts".

fMRI data has a lot of features and fewer examples. Hence, it is desirable to reduce the number of features using feature selection techniques. For our purpose the voxels will be the features to extract. We want to know "how important the voxels of a certain region are, according to the task. The strategy used is voxel discriminability. For each voxel and considered cognitive state, an analysis of variance (ANOVA) is performed comparing the fMRI activity of the voxel in examples belonging to the different stimuli of interest. More concretely, the method chosen is the *one-way analysis of variance*, with a test statistic called *F ratio*. A certain number of voxels can be now selected by choosing the ones with larger f-values. More detail information about the data extraction is described in [16].

Finally, the extracted features are projected onto a hemisphere through a line joining the center of the brain to a point on the surface, and intersecting the top half of a circumscribed sphere (Figure 1).

4. BRAIN AESTHETICS

In order to sonify the extracted features (section 3) into music, we have taken several aesthetic considerations and various levels of abstraction. We want to bring harmony to the formal features, while revealing new insights into reality. The dimensionality of the brain and its activity in terms of voxel energy should be directly perceivable. It is a deliberate choice to turn the brain into a musical instrument by presenting the data as directly as possible. The intention is to explore the aesthetic potential not by transforming the data beyond the recognizable, but by choosing the correct sonification method. The work attempts to display technical data,

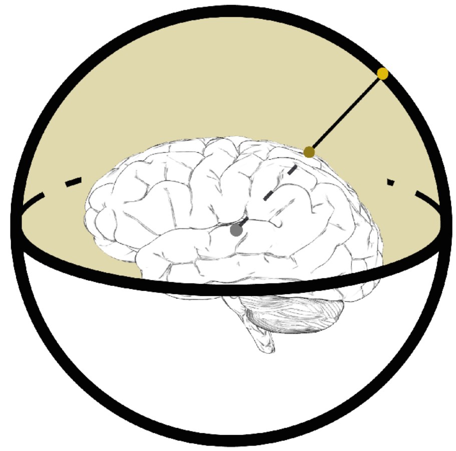

Figure 1: 3D projection of the features onto a virtual hemisphere. The grey dot represents both the center of the brain and the center of the sphere. The dark yellow dot represents the feature to be projected into the light yellow dot.

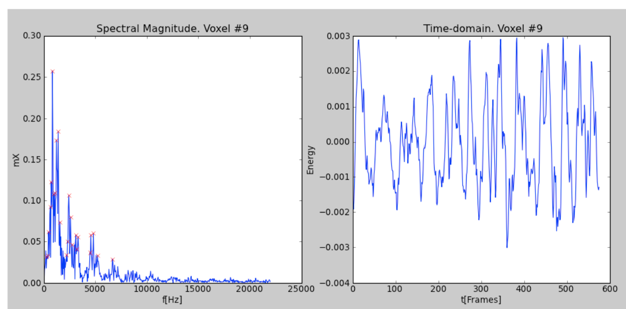

Figure 2: Time– Frequency representation from a voxel. The right graphic corresponds to the time domain, while the left graphic represents the magnitude of the voxel's spectral analysis.

while conveying feelings and make the experience enjoyable, both in terms of sonification and of spatial composition.

The first assumption is to consider each voxel as an audio sample to derive a base material to be later sonified. The approach taken can be somewhat compared to methods used in the spectral school [41]. Each voxel measurement contained around 500 samples. This is sufficient to extract a frequency analysis of the respective voxel. In the time domain, we normalize the samples and extract their mean. Afterwards proceed with the spectral analysis of the signal, and determine the most relevant frequencies. An example of a single voxel can be seen in Figure 2.

The most relevant frequencies are then mapped to the corresponding pitches. This results numerous scales and chords, each relating to different groups of the brain. Using these scales as compositional models, we can then score instrumental passages, which are performed and recorded as the base audio. Each passage contains a chord in its temporal center that represents the respective voxel as a whole. Compositionally, we then interpolate between the voxels.

This first step demonstrates the highest level of abstraction.

While each scale and chord represents a single voxel essentially, the amount of transformation done is beyond the recognizable. But the intention here was not to sonify the brain but to derive sound material that is only *based* on its data. The tonal composition itself is coarse, because, as it will be described further down, the spatial composition is able to distort the original sound to such degrees that it may claim the complete work for itself. Nevertheless, we retain the freedom to steer this basic material to our liking and create a well sounding instrumental composition.

4.1. Rapid panning modulation synthesis

On a less abstract representation of the brain lies the spatial composition. While the tonal composition was a necessity, the spatial considerations are the main focus of this work. The aesthetic followed here is similar to that of Hagan [35], in the sense that it creates a single engulfing sound. But while Hagan works with textures so dense that she describes a parallax between perceiving a single grain of sound and the complete, surrounding agglomerate as a single entity, we chose to pan our base material at speeds beyond the perception of motion.

In fact, the method described here is similar to how Stockhausen describes a technique used in *Sirius* (1975-77): "Sirius is based entirely on a new concept of spatial movement. The sound moves so fast in rotations and slopes and all sorts of spatial movements that it seems to stand still, but it vibrates. It is an entirely different kind of sound experience, because you are no longer aware of speakers, of sources of sound – the sound is everywhere, it is within you. When you move your head even the slightest bit, it changes color, because different distances occur between the sound sources"[2]

This above quote describes the sensation of the rapid panning modulation synthesis quite well. Once beyond the point that the motion of the source can be detected, the sound becomes static while still maintaining pulsating sensation. It becomes a single sound that is inherently spatial, meaning that the sound *becomes the space* as you cannot localize it any more even though is obviously present. Therefore, this work is not concerned about spatializing sounds in the traditional sense, it is about creating and working with *spatial sounds*. Furthermore, due to the omnipresence of the sound, the movement of the audience member inside lets him experience the sonorities differently. Hence, exploring both the auditory space and sound becomes one.

For *Sirius*, Stockhausen used a directional, rotary speaker to create this type of movement. Instead, for this work, we created a Max/MSP patch that is able to pan between an arbitrary amount of virtual loudspeakers on a sphere. This means that the actual sound source, as seen from the spatialization technology, is not moved, but the sound is sent to different virtual sources based on equal distance panning. This is done in both azimuth and elevation and the source signal can be panned by two modulation signals simultaneously in any direction.

[2]Stockhausen, as quoted in [26]

Figure 3: A set of notes extracted from the analysis in Figure 2.

Also, once the panning speed exceeds $\sim 20Hz$ in either direction sound synthesis is applied. The resulting effect is similar to amplitude modulation, but demonstrates significant differences. For one, the source sound theoretically is present in one to two speakers at a time. This means that the synthesis is a bit more complex and rich in high frequencies. More significantly, though, the rapid panned synthesis is *highly spatial*, meaning, it can not live without its space. If all virtual sources are moved into one another the synthesis is removed and the original sound surfaces.

4.2. Connecting the brain

Using a virtual loudspeaker setup instead of sending audio to the speakers directly brings many advantages. For one, the software that drives the artwork is independent of respective speaker setup on site. Furthermore, virtual speakers can be created at will and each speaker introduces a point of entry for further synthesis methods.

Having the complex spatial sound, we decided to introduce the voxels into the spatialization process by connecting their energy values directly with a filter. As the voxels were grouped into 50 regions on the half sphere, we used 50 virtual speakers, each with an individual processing unit. The voxel energy information was sent between two computers over the Opend Sound Control protocol, being normalized between $[0, 1]$. The information could then easily be rescaled to a respective center frequency. Additionally, the degree of change can be measured within a window and scaled to a meaningful Q-value.

The result is a colored, fully engulfing and pulsating sound. As the center frequencies of the many filters follow the energy values of each respective voxel region, the coloring of the whole construct is in constant shift, following the progression of the brain itself. Surprisingly, the sound was mostly uniform at first. But individual voxels started to break away from the large background, creating new auditory streams. Their position in space plays a key role. While a small number of voxels break away on their own, they create choreographies together, working with one another, against each other, from different points on the compass or next to each other, exchanging timbres and fusing to a single auditory stream.

5. CONCLUSIONS AND FUTURE WORK

As seen in the paper we have implemented a three dimensional sonification of fMRI brain data with aesthetic intentions. The brain data was filtered and projected onto a sphere. The sonification process was mainly carried out in two steps: first we derived pitched material from a quite abstract spectral analysis of each voxel, composing a base material from this pool of information. We then spatialized this data with a rapid panning technique creating a fully engulfing sound to represent the base material of the brain. Individual filters for each voxel then directly represents the activity and invites the visitor to explore this world with his own spatial hearing.

Visitors have reported a soothing, almost hypnotizing affection. Most were aesthetically pleased. The reduction of pitched material and other traditional musical parameters shifted the focus of the spatial interplay of each voxel successfully and made the composition/installation a true immersive experience.

For future work, we intend to investigate the interplay between different individuals whose fMRI data was recorded. Also, there are many points at which the sonification may tap in using different, higher level features. For example, as it can be seen in Figure 2, there is a clear low frequency oscillation in the time domain representation of a voxels energy development, which could be separated from the smaller fluctuations when subtracted, and used as two separate sonification methods. Also, we would like to group different meaningful regions of the brain, such as cerebellum, together, which could prove useful for macro-parameters or similar.

6. REFERENCES

[1] I. Xenakis, *Formalized music : thought and mathematics in composition.* Stuyvesant, NY: Pendragon Press, 1992.

[2] A. Schoon and F. Dombois, "Sonification in music," in *Proc. of the 15th Int. Conf. on Auditory Display*, Copenhagen, Denkmark, May 2009, pp. 76–78.

[3] D. A. Maluf and P. B. Tran, "Sensing super-position: Human sensing beyond the visual spectrum," in *IEEE International Conference on Information Reuse and Integration*, 2007, pp. 595–602.

[4] T. Hermann, M. Hansen, and H. Ritter, "Combining Visual and Auditory Data Exploration for finding structure in high-dimensional data," *Multimedia Systems*, 2001.

[5] S. Barrass and G. Kramer, "Using sonification," *Multimedia Systems*, vol. 7, no. 1, pp. 23–31, 1999. [Online]. Available: http://dx.doi.org/10.1007/s005300050108

[6] K. Vogt, T. Bovermann, P. Huber, and A. de Campo, "Exploration of 4d-data spaces. sonification in lattice qcd," in *International Conference on Auditory Display*, Paris, France, June 2008.

[7] F. Grond, S. Janssen, S. Schirmer, and T. Hermann, "Browsing rna structures by interactive sonification," in *Proceedings of ISon 2010, 3rd Interactive Sonication Workshop*, Copenhagen, Denkmark, 2010.

[8] D. O. R. Michael Winters, Andrew Blaikie, "Simulating the Electroweak Phase Transition: Sonification of Bubble Nucleation," in *Proceedings of the 17th International Conference on Auditory Display (ICAD2011)*, Budapest, Hungary, 2011.

[9] N. Bearman, "Using sound to represent uncertainty in future climate projections for the United Kingdom," in *Proceedings of the 17th International Conference on Auditory Display (ICAD2011)*, Budapest, Hungary, 2011.

[10] R. L. Alexander, J. A. Gilbert, M. Simoni, T. H. Zurbuchen, A. Arbor, and D. A. Roberts, "Audification as a Diagnostic Tool for Exploratory Heliospheric Data Analysis," in *Proceedings of the 17th International Conference on Auditory Display (ICAD2011)*, Budapest, Hungary, 2011, pp. 24–27.

[11] E. D. Adrian and B. H. C. Matthews, "The Berger Rhythm: potential changes from the occipital lobes in man," *Brain*, vol. 57, pp. 355–384, 1934.

[12] T. Hermann, P. Meinicke, H. Bekel, H. Ritter, H. M. Mueller, and S. Weiss, "Sonifications for eeg data analysis," in *Proceedings of the 8th International Conference on Auditory Display (ICAD2002)*, R. Nakatsu and H. Kawahara, Eds., Kyoto, Japan, 2002. [Online]. Available: Proceedings/2002/HermannMeinicke2002.pdf

[13] A. Hunt and T. Hermann, "THE IMPORTANCE OF INTERACTION IN SONIFICATION," in *Proceedings of the 10th Meeting of the International Conference on Auditory Display*, Sydney, Australia, 2004.

[14] T. Hermann, G. Baier, U. Stephani, and H. Ritter, "Vocal sonification of pathologic eeg features," in *Proceedings of the 12th International Conference on Auditory Display (ICAD2006)*, London, UK, 2006, pp. 158–163. [Online]. Available: Proceedings/2006/HermannBaier2006.pdf

[15] G. Baier, T. Hermann, and U. Stephani, "Multi-channel sonification of human eeg," in *Proceedings of the 13th International Conference on Auditory Display (ICAD2007)*, G. P. Scavone, Ed. Montreal, Canada: Schulich School of Music, McGill University, 2007, pp. 491–496. [Online]. Available: Proceedings/2007/BaierHermann2007.pdf

[16] I. Gomez and R. Ramirez, "A data sonification approach to cognitive state identification," in *Proceedings of the 17th International Conference on Auditory Display (ICAD2011)*, Budapest, Hungary, 2011.

[17] D. Wu, C. Li, Y. Yin, C. Zhou, and D. Yao, "Music composition from the brain signal: representing the mental state by music." *Computational intelligence and neuroscience*, 2010. [Online]. Available: http://dx.doi.org/10.1155/2010/267671

[18] S. Barrass, M. Whitelaw, and F. Bailes, "Listening to the Mind Listening: An Analysis of Sonification Reviews, Designs and Correspondences," *Leonardo Music Journal*, vol. -, pp. 13–19, 2006. [Online]. Available: http://www.mitpressjournals.org/doi/abs/10.1162/lmj.2006.16.13

[19] R. Melara and T. OBrien, "Interaction between synesthetically corresponding dimensions," *Journal of Experimental Psychology: General*, vol. 116, pp. 323–336, 1987.

[20] A. Einbond and D. Schwarz, "Spatializing timbre with corpus-based concatenative synthesis," in *Proceedings of the International Computer Music Conference*, New York, NY USA, 2010.

[21] D. Smalley, "Space-form and the acousmatic image," *Organised Sound*, vol. 12, no. 01, pp. 35–58, 2007.

[22] M. A. Harley, "Space and spatialization in contemporary music: History and analysis, ideas and implementations," Ph.D. dissertation, McGill University, PDF Reprint under Maja Trochimzyck, Moonrise Press, Los Angeles, California, 2011, 1994.

[23] R. Normandeau, "Timbre Spatialisation: The medium is the space," *Organised Sound*, vol. 14, no. 03, pp. 277–285, 2009.

[24] G. Theile, "Wave field synthesis – a promising spatial audio rendering concept," in *Proc. of the 7th Int. Conference on Digital Audio Effects*, Neaples, Italy, 2004, pp. 125–132.

[25] V. Pulkki, "Spatial sound generation and perception by amplitude panning techniques," PhD Thesis, Helsinki University of Technology, 2001.

[26] E. Bates, "The Composition and Performance of Spatial Music," Ph.D. dissertation, Trinity College Dublin, 2009.

[27] B. Zelli, "Reale und virtuelle Räume in der Computermusik," Ph.D. dissertation, Technische Universität Berlin, 2001.

[28] R. Zvonar, "A history of spatial music," *eContact!*, vol. 7, no. 4, 2006. [Online]. Available: http://cec.concordia.ca/econtact/Multichannel/spatial_music.html

[29] J. W. Solomon, "Spatialization in music: The analysis and interpretation of spatial gestures," Ph.D. dissertation, University of Georgia, May 2007.

[30] M. Trochimczyk, "From circles to nets: On the signification of spatial sound imagery in new music," *Computer Music Journal*, vol. 25, no. 4, pp. 39–56, 2001.

[31] H. Brant, "The uses of antiphonal distribution and polyphony of tempi in composing," *American Composer's Alliance Bulletin*, vol. 4, no. 3, pp. 13–15, 1955.

[32] V. Lombardo, A. Valle, J. Fitch, K. Tazelaar, and S. Weinzierl, "A Virtual-Reality Reconstruction of Poème Électronique Based on Philological Research," *Computer Music Journal*, vol. 33, no. 2, pp. 24–47, 2009.

[33] J. Smalley, "Gesang der Jünglinge: History and Analysis," 2000. [Online]. Available: http://www.music.columbia.edu/masterpieces/notes/stockhausen/GesangHistoryandAnalysis.pdf

[34] M. Fowler, "The Ephemeral Architecture of Stockhausen's Pole für 2," *Organised Sound*, vol. 15, no. 03, pp. 185–197, Oct. 2010.

[35] K. Hagan, "Textural Composition and its Space," in *Sound and Music Computing Conference: sound in space-space in sound*, Berlin, Germany, 2008.

[36] A. S. Bregman, *Auditory Scene Analysis: The Perceptual Organization of Sound.* Cambridge, MA, USA: The MIT Press, 1990.

[37] B. Arons, "A Review of The Cocktail Party Effect," *Journal of the American Voice I/O Society*, vol. 35–50, no. July, pp. 701–705, 2001.

[38] M. Chion, "The three listening modes," in *Audio/Vision: Sound on Screen.* New York, NY, USA, availbale online: http://helios.hampshire.edu/~hacu123/papers/chion.html: Columbia University Press, 1994.

[39] B. Blesser and L.-R. Salter, *Spaces Speak, are you listening?* Cambridge, MA, USA: MIT Press, 2007.

[40] J. a. Grahn and J. B. Rowe, "Feeling the beat: premotor and striatal interactions in musicians and nonmusicians during beat perception." *The Journal of neuroscience : the official journal of the Society for Neuroscience*, vol. 29, no. 23, pp. 7540–8, Jun. 2009. [Online]. Available: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=2702750\&tool=pmcentrez\&rendertype=abstract

[41] G. Grisey, "Tempus ex machina: A composer's reflections on musical time," *Contemporary Music Review*, vol. 2, pp. 239–275, 1987.